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**Optimization of a highly efficient supersonic COIL**  
**with supersonic mixing of iodine and oxygen**

Contract No. 033055

BGU Internal Contract No. 82188

**Final Report for the Period**

**01.07.2003 - 30.06.2004**

**Principal Investigators: Dr. Boris Barmashenko and Prof. Zamik Rosenwaks**

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## I. Abstract

We report on a detailed parametric study of an extremely efficient supersonic chemical oxygen-iodine laser (COIL) with supersonic mixing of iodine and oxygen. As a result of optimization of the supersonic mixing scheme, output power exceeding 0.6 kW with chemical efficiency of ~40% was obtained in a 5 cm gain length for Cl<sub>2</sub> flow rate of ~17 mmole/s. 40% efficiency is the highest reported chemical efficiency of any supersonic COIL and it is close to the upper theoretical limit of the COIL chemical efficiency.

The following projects have been carried out during the reported period:

1. Measurements of the gain, temperature and density of I<sub>2</sub> ([I<sub>2</sub>]) for nozzles with transonic and supersonic mixing and different iodine injection angles.
2. Measurements of the lasing power for new supersonic nozzles with different injection location along the flow and for different throat heights and achievement of 40% chemical efficiency
3. Design of a new optical system for measurements of [I<sub>2</sub>] using 488 nm probe beam from a blue LED.
4. Design and manufacturing of a 10 cm gain-length laser set-up.
5. Development of 3D CFD model for our laser.

## II. Scientific background and objectives of the project

The chemical oxygen iodine laser (COIL)<sup>1,2</sup> is the most efficient and the shortest wavelength high-energy chemical laser existing to date. A very important parameter of the COIL is the chemical efficiency  $\eta_{chem}$  defined as the number of emitted photons per number of chlorine molecules passed through the O<sub>2</sub>(<sup>1</sup>Δ) generator. Maximum values of  $\eta_{chem}$ , about 29.5%, were obtained for subsonic<sup>3</sup> and transonic<sup>4</sup> mixing schemes. For supersonic mixing scheme smaller  $\eta_{chem}$ , 25%, was achieved<sup>5</sup>.

Recently we have briefly reported on a small-scale (5-cm gain length) COIL with a supersonic mixing scheme that operates with a record-breaking efficiency of 33%.<sup>6</sup> The objectives of the present project were a detailed parametric study of this extremely efficient laser, optimization of the oxygen/iodine supersonic mixing scheme in order to achieve maximum laser power and chemical efficiency and measurements of the spatial distributions of the gain, temperature and I<sub>2</sub> density across the flow in order to understand the mixing mechanisms and to compare the experimental results with CFD computations.

### III. Description of the results

#### 1. Measurements of the gain, temperature and density of $I_2$ ( $[I_2]$ ) for nozzles with transonic and supersonic mixing and different iodine injection angles

Spatial distributions of the gain, temperature and density of molecular iodine across the flow were measured for a nozzle with transonic injection of iodine (nozzle No. 1) and a nozzle with supersonic injection of iodine at  $74^\circ$  to the primary flow (nozzle No. 2). The results were compared with those obtained for a nozzle with supersonic injection at  $45^\circ$  to the primary flow (nozzle No. 3) where we got 33% chemical efficiency<sup>P6</sup>. The distributions were studied as a function of the secondary nitrogen and iodine flow rates ( $nN_2$  and  $nI_2$ ). Maximum value of the gain ( $\sim 0.75\%/cm$ ) was achieved for nozzle No.3. This value of the gain is about 1.5 times larger than the maximum gains achieved for nozzles 1 and 2 ( $\sim 0.4$ - $0.5\%/cm$ ). For small secondary nitrogen flows (underpenetrated jets), the gain distribution across the flow has a bimodal structure with two peaks beside the centerline of the jets. The  $[I_2]$  in "cold" runs where singlet oxygen is replaced with  $N_2$  has a similar bimodal distribution. Increase of  $nN_2$  results in merging of the two peaks and the gain distribution has one peak at the flow centerline. Maximum values of the power for different injectors is achieved at  $nN_2$  corresponding to weakly underpenetrated jets when the two peaks of the gain and of  $[I_2]$  almost merge. It should be noted that the values of  $nN_2$  and hence  $nI_2$  corresponding to the maximum power for nozzle No. 3 are larger than for nozzles No. 1 and 2. Larger value of the optimal  $nI_2$  results in larger value of the gain and power for nozzle No. 3.

#### 2. Measurements of the lasing power for new supersonic nozzles with different injection location along the flow and different throat heights and achievement the record-breaking 40% chemical efficiency

To optimize the supersonic mixing scheme we measured the power for a series of new supersonic nozzles with different locations of the iodine injection holes. Some of these nozzles are profiled to avoid shock waves and they have different locations of the iodine injection holes in the supersonic section of the flow. It is also possible to change the nozzle throat height (5 mm or 8 mm). For these nozzles a series of experiments was carried out where we measured lasing power in order to find the nozzle for which the power is maximal (see Table I). We used nozzle No.3 for which we got 33% chemical efficiency<sup>6</sup> as a reference. In our experiments we tested four new nozzles. Three of the nozzles were profiled with a  $45^\circ$  angle between the primary and secondary flow and different locations of non-staggered injection holes along the flow. The flow height  $H$  at

the injection location is 6.5, 7.5 and 8.75 mm for nozzles No. 4, 5 and 6, respectively. A non-profiled nozzle, No. 7, with a throat height of 8 mm, larger than the 5 mm throat height of nozzles No. 1-6, was also tested.

In order to decrease the flow temperature in the resonator the iodine-oxygen mixing system was not electrically heated by special resistors mounted into the mixing block as we usually did in our previous experiments. Another important feature of the present experiments is that we paid special attention to the mirrors quality and alignment. In particular to achieve high power the mirrors were accurately aligned before each laser run.

Table I. Maximum power and chemical efficiency for different supersonic mixing schemes. Nozzles No. 3 – 6 have 5 mm throat height; nozzle No.3 has staggered injection holes, and nozzles No. 4-6 have non-staggered injection holes

Run No.	Nozzle number and description	$n\text{Cl}_2$ [mmole/s]	$n\text{N}_2$ [mmole/s]	$n\text{I}_2$ [mmole/s]	Pressure in the JSOG [Torr]	Pressure in the resonator [Torr]	Power [W]	Chemical efficiency [%]
1	No.3, reference	17.4	28	0.6	14.6	2.4	517	32.7
2	No.4, profiled, H = 6.25 mm	17.3	17	0.31	14.3	2.0	587	37.2
3	No.5, profiled, H = 7.5 mm	17.4	28	0.39	15.5	2.3	600	37.9
4	No.6, profiled, H = 8.75 mm	17.3	28	0.36	14.6	2.2	553	35
<b>5</b>	<b>No.7, non-profiled, 8 mm throat height</b>	<b>17.4</b>	<b>28</b>	<b>0.45</b>	<b>13.3</b>	<b>2.3</b>	<b>627</b>	<b>39.6</b>

The results of the power measurements are presented in Table I. The maximum values of the chemical efficiencies obtained for profiled nozzles Nos. 4, 5 and 6 with 5 mm throat height (runs 2 to 4, respectively) are  $\sim 37\%$ ,  $38\%$  and  $35\%$ , respectively. They are larger than the  $\sim 33\%$  efficiency achieved for nozzle 3 in <sup>6</sup> (run 1). It was difficult to find which of the nozzles (No. 4 – 6) is best since the power strongly depends on both the mirror

quality which tends to deteriorate from run to run and on the mirrors' alignment. Analysis of other results (not presented in Table I) shows that for the nozzles with 5 mm throat height, the dependence of the power and chemical efficiency on the injection location along the flow is very weak. However, the power obtained in run 5 for nozzle No.7 with 8 mm throat height was higher than that obtained in run 3 for nozzle No. 5 with a smaller (5 mm) throat height. In both runs we used the same mirrors with total transmission  $T=1\%$ . Hence, increase of the nozzle throat height results in power increase. The reason for higher power obtained for nozzle No.7 is smaller generator pressure due to larger throat height resulting in smaller energy losses of singlet oxygen.

Maximum power of 627 W with chemical efficiency of about 40% was achieved for nozzle No. 7. 40% efficiency is the highest reported chemical efficiency of a supersonic COIL. It is much larger than the 33% efficiency reported recently by us in <sup>6</sup> and very recently in <sup>7</sup> and is close to the upper theoretical limit of the COIL chemical efficiency.

### 3. Design of a new optical system for measurements of $[I_2]$ using 488 nm probe beam from a blue LED

We decided to probe  $[I_2]$  with a 488 nm beam from a blue LED rather than using the 540 nm green He-Ne laser beam as we did before. The reason is that the 488 nm transition of  $I_2$  lies in the continuous part of the absorption spectrum whereas the 540 nm signal probes individual rovibronic lines of  $I_2$ . As a result the absorption cross section around 488 nm is not sensitive to variations in the temperature and ground-state rovibrational population. Since the blue LED signal is weaker than that of the green He-Ne, a new optical system is being designed to probe the  $I_2$  across the flow. For this system all the optical components (the collimators, beamsplitters, chopper and detectors) will be moved by a linear stage across the gas flow. As a result a very accurate alignment should be possible.

### 4. Design and manufacturing of a 10 cm gain-length laser set-up

We finished the design and manufacturing of the new 10 cm length singlet oxygen generator. Manufacturing of a new resonator and diagnostic cell is underway. There are two advantages of the larger gain length: (1) sensitivity of the absorption spectroscopy methods increases making it easier to measure densities of different species in the flow; (2) it is possible to use mirrors with smaller reflection coefficient for which the power could be less dependent on the mirror quality.

#### 5. Development of 3D CFD model for our laser

We developed and run a 3D CFD model for our laser in cooperation with Dr. M. Endo of Tokai University (Japan). The model is based on the commercial Phoenix code and describes the chemistry and gas dynamics in the COIL active medium. In the first stage of the modeling we compared the calculated gas dynamic parameters to the experimental measurements without taking into account chemical reactions. Good agreement between the calculated and measured  $I_2$  distributions across the flow was found for different secondary  $N_2$  flow rates corresponding to underpenetrated and overpenetrated jets. Work is in progress in order to improve the agreement.

#### IV. Conclusions and recommendations

Optimization of the iodine mixing system made it possible to increase substantially the chemical efficiency of the COIL. As a result output power exceeding 0.6 kW with chemical efficiency of ~40% was obtained in a 5 cm gain length COIL. 40% efficiency is the highest reported chemical efficiency of a supersonic COIL and is close to the upper theoretical limit of the COIL chemical efficiency. To achieve optimal power the supersonic throat height was increased from 5 mm to 8 mm which resulted in smaller pressure in the subsonic section of the flow and hence in smaller energy losses of the singlet oxygen molecules. It was observed that the power strongly depends on the mirrors quality and alignment. That is why larger, stable output power can be obtained more easily by up-scaling the laser to 10 cm gain length which is underway in our laboratory. Another possible way to increase the power and chemical efficiency is to optimize the iodine injection location along the flow for the nozzle with 8 mm throat height. Further diagnostic measurements of the gain, temperature and iodine dissociation fraction for different supersonic mixing schemes, in particular for nozzles No. 4-7, will definitely provide for better understanding of the chemical and gas-dynamical processes in the COIL and will result in finding new possible ways for optimization of the COIL.

#### V. References

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7. M. Endo, Tatsuo Osaka and Shuzaburo Takeda, " High-efficiency chemical oxygen-iodine laser using a streamwise vortex generator," *Appl. Phys. Lett.*, vol. 84, pp. 2983-2985, 2004.

## VI. Supplements

### 1. List of the people participating in the project

The list includes only the people participating in the research (it does not include the workers of different workshops that helped in building and maintenance of the experimental setup):

Prof. Zamik Rosenwaks, principal investigator

Dr. Boris Barmashenko, principal investigator

Mr. Victor Rybalkin, investigator (Ph. D. student)

Mr. Arje Katz, investigator (Ph. D. student)

### 2. List of the technical documents during the reported period

The technical documents that appeared during the reported period include three quarterly reports submitted to the EOARD and the papers published or submitted for publication in 2003-2004. Below is the list of the papers:

1. B. D. Barmashenko, V. Rybalkin, A. Katz, E. Bruins, D. Furman and S. Rosenwaks, "Mechanisms of COIL operation: experiment and modeling", in 14th International Symposium on Gas Flow and Chemical Lasers and High Power Laser Conference, Proc. SPIE, 2003, vol. 5120, pp.308-315.

2. B.D. Barmashenko and S. Rosenwaks, "Chemical Lasers: COIL", in Handbook of Laser Technology and Applications, Institute of Physics, Vol. 2, pp 861-880 (2003).

3. B. D. Barmashenko, V. Rybalkin, A. Katz and S. Rosenwaks, "Parametric study of the Ben-Gurion University efficient chemical oxygen-iodine laser", in High-Power Laser Ablation V symposium, Proc. SPIE, 2004, in press.

#### VI. Acknowledgments

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